Determining Heavy Mass Parameters in SUSY SO(10)

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The high precision expected in e^+e^- collider experiments allows the reconstruction of the fundamental supersymmetric scalar mass parameters at the unification scale and the D-terms related to the breaking of GUT symmetries. We investigate the potential of this method in the lepton sector of SO(10) breaking directly to the SM gauge group. SO(10) naturally incorporates right-handed neutrino superfields in a seesaw scenario. The mass of the third generation heavy neutrino can also be estimated with our method.

The observation of neutrino oscillations has provided experimental proof for non-zero neutrino masses [2]. When right-handed neutrinos, not carrying any Standard Model gauge charges, are included in the set of leptons and quarks, the symmetry group SO(10) is naturally suggested as the grand unification group [3]. For theories formulated in a supersymmetric frame to build a stable bridge between the electroweak scale and the Planck scale, a scalar R-neutrino superfield is added to the spectrum of the minimal supersymmetric standard model. A natural explanation of the very light neutrino masses in relation to the electroweak scale is offered by the seesaw mechanism [4]. For right-handed Majorana neutrino masses $M_{\nu_{Ri}}$ in a range close to the GUT scale, small neutrino masses can be generated quite naturally by this mechanism: $m_{\nu_i} \sim m_{q_i}^2/M_{\nu_{Ri}}$, with m_{q_i} denoting up-type quark masses.

We investigate a one-step breaking scenario in which SO(10) is directly broken to the SM gauge group at the unification scale Λ_U. The SO(10) scalar soft SUSY breaking sector is parametrized by the gravity induced mass parameters m_{16} for the matter superfields and m_{10_1}, m_{10_2} for two Higgs superfields. Starting at Λ_U, the mass parameters evolve, following the renormalization group (RG), down to the electroweak scale. Once the masses of supersymmetric particles are measured, the RG evolution from the Tera-scale upwards will allow us to reconstruct the physics scenario at the GUT scale [5, 6]. The matter superfields of the three generations belong to 16-dimensional representations of SO(10) and the standard Higgs superfields to two 10-dimensional representations, while a Higgs superfield in the 126-dimensional representation generates the Majorana masses for the right-handed neutrinos. The couplings of this 126 Higgs to the other matter fields are assumed to be small. The Higgs sector of this model may be expanded to solve certain SO(10) GUT problems such as doublet-triplet splitting and proton decay, but such an expansion does not affect the present study significantly.

It follows from the Higgs-{10} SO(10) relation that $Y_\nu = Y_u$ between the neutrino and up-type Yukawa matrices at Λ_U. The effective mass matrix of the light neutrinos is constrained by the results of the oscillation experiments, $m_\nu = U^*_{MNS} \cdot diag(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}) \cdot U^\dagger_{MNS}$. We assume the normal hierarchy for the light neutrino masses, and for the MNS mixing matrix the tri-bimaximal form. From the seesaw relation $M_{\nu_R} = Y_\nu m_\nu^{-1} Y_\nu^T \cdot v_u^2$, the heavy

Majorana R-neutrino mass matrix M_{ν_R} can finally be derived as

$$M_{\nu_R} \approx diag(m_u, m_c, m_t) m_\nu^{-1} diag(m_u, m_c, m_t). \tag{1}$$

For normal hierarchy, m_{ν_3} and m_{ν_2} are given by the squared mass differences measured in neutrino oscillation experiments. Solving Eq. (1) the $M_{\nu_{Ri}}$ spectrum is then predicted by the up-quark masses $m_{u,c,t}$ and the lightest neutrino mass m_{ν_1} at the GUT scale. Consequently, the mass spectrum of the R-neutrinos is strongly ordered in SO(10) with minimal Higgs content,

$$M_{\nu_{R3}} : M_{\nu_{R2}} : M_{\nu_{R1}} \sim m_t^2 : m_c^2 : m_u^2. \tag{2}$$

The Yukawa mass matrix squared, which determines the connection of the slepton masses in the third generation at low and high scales, is dominated by the 33 element, $\left(Y_\nu^\dagger Y_\nu\right)_{33} \approx m_t^2(\Lambda_U)/v_u^2 \approx 0.3$, while the other elements are suppressed to a level of 10^{-2} down to 10^{-5}.

The scalar mass parameters at the unification scale will be assumed universal for the SO(10) representations. However, the breaking of the rank-5 SO(10) symmetry group to the lower rank-4 SM group generates GUT D-terms D_U violating the scalar mass universality at Λ_U. To leading logarithmic order, the solutions of the RG equations, the masses of the selectrons and the L-type e-sneutrino, can be expressed in terms of the high scale parameter M_0, the universal gaugino mass parameter $M_{1/2}$ and the GUT and electroweak D-terms, D_U and $D_{EW} = 1/2 M_Z^2 \cos 2\beta$, respectively:

$$\begin{aligned} m_{\tilde{e}_R}^2 &= M_0^2 + D_U + \alpha_R M_{1/2}^2 - \tfrac{6}{5} S' - 2 s_W^2 D_{EW}, \\ m_{\tilde{e}_L}^2 &= M_0^2 - 3 D_U + \alpha_L M_{1/2}^2 + \tfrac{3}{5} S' - c_{2W} D_{EW}, \\ m_{\tilde{\nu}_{eL}}^2 &= M_0^2 - 3 D_U + \alpha_L M_{1/2}^2 - \tfrac{6}{5} S' + D_{EW}. \end{aligned} \tag{3}$$

The coefficients α_L and α_R can be calculated from the gaugino/gauge boson loops, and a numerical integration yields $\alpha_R \approx 0.15$ and $\alpha_L \approx 0.5$. The universal gaugino mass parameter $M_{1/2}$ can be pre-determined in the chargino/neutralino sector. The non-universal initial conditions due to the D-terms generate the small generation-independent corrections $S' = -4 D_U \alpha_1(\tilde{M})/\alpha_1(\Lambda_U)$ from the GUT to the Tera-scale $\tilde{M}$.

Representations of the scalar masses in the *third generation* are complemented by $\nu_{R\tau}$ loops coupled by Yukawa interactions with the L and R fields. The masses of the third generation are shifted relative to the masses of the first two generations by two terms [5, 6]:

$$\begin{aligned} m_{\tilde{\tau}_R}^2 &= m_{\tilde{e}_R}^2 + m_\tau^2 - 2\Delta_\tau, \\ m_{\tilde{\tau}_L}^2 &= m_{\tilde{e}_L}^2 + m_\tau^2 - \Delta_\tau - \Delta_{\nu_\tau}, \\ m_{\tilde{\nu}_{\tau L}}^2 &= m_{\tilde{\nu}_{eL}}^2 - \Delta_\tau - \Delta_{\nu_\tau}. \end{aligned} \tag{4}$$

The shifts Δ_τ and Δ_{ν_τ}, generated by loops involving charged lepton and neutrino superfields, respectively, are predicted by the renormalization group in the SO(10) scenario,

$$\Delta_\tau \approx \frac{m_\tau^2(\Lambda_U)}{8\pi^2 v_d^2} \left(3M_0^2 + A_0^2\right) \log \frac{\Lambda_U^2}{M_Z^2}, \tag{5}$$

$$\Delta_{\nu_\tau} \approx \frac{m_t^2(\Lambda_U)}{8\pi^2 v_u^2} \left(3M_0^2 + A_0^2\right) \log \frac{\Lambda_U^2}{M_{\nu_{R3}}^2}. \tag{6}$$

Anticipating measurements of high precision at the ILC, such an SO(10) scenario can be investigated in all its facets. As a concrete example, we study the following LR-extended scenario which is close to SPS1a/a′ [7, 8]:

$$\begin{aligned} M_0 &= 90\ \text{GeV} \\ M_{1/2} &= 250\ \text{GeV} \\ A_0 &= -640\ \text{GeV} \\ D_U &= (30\ \text{GeV})^2 \\ \tan\beta &= 10 \\ \text{sign}\mu &= + \\ M_{\nu_{R3}} &= 7.21 \cdot 10^{14}\ \text{GeV}. \end{aligned} \qquad (7)$$

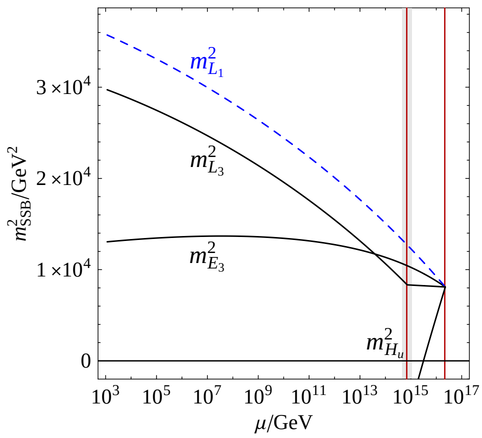

Figure 1: Evolution of scalar mass parameters between Λ_U and the Tera-scale for $D_U = 0$ with a r.h. neutrino mass $M_{\nu_{R3}} \approx 10^{15}$ GeV.

In this scenario, the masses of the charged sleptons can be measured with high precision in slepton pair production at ILC [9], while the sneutrino masses can be determined accurately from the decays of charginos [5]. Taking into account squark mass measurement at the LHC in addition, a global analysis leads to an accurate determination of A_0 [7, 11].

The measurement of the slepton and sneutrino masses of the first two generations allows us to extract the common scalar parameter M_0 as well as the D-term D_U. The approximate relations are given in Eq. (4). Including the complete one-loop and the leading two-loop corrections, the evolution of the scalar mass parameters is displayed in Figure 1. The right-handed neutrino mainly affects the evolution of the mass parameter m^2_{L3} in the third generation. The characteristic kink in the evolution between m^2_{L3} and m^2_{L1} is exemplified in Figure 1 for a right-handed neutrino mass $M_{\nu_{R3}}$ of about 10^{15} GeV.

With the experimental measurement errors, the high-scale parameters can be calculated. With the RG evolution equations are evaluated to 2-loop order [12], a global analysis indicates that the high-scale parameters M_0 and $D_U^{1/2}$, can be reconstructed at per-mill to per-cent accuracy, $M_0 = (90 \pm 0.34)$ GeV, $D_U^{1/2} = 30 \pm 0.7$ GeV.

The right-handed neutrino mass is fixed by the intersection of the parameter Δ_{ν_τ}, Eq. (6), with the measured value $\Delta^{exp}_{\nu_\tau} = (4.7 \pm 0.4) \cdot 10^3\ \text{GeV}^2$ extracted from the slepton masses. This is shown in Figure 2. The effect of the heavy ν_{R3} mass can indeed be traced back from measured slepton masses in universal supersymmetric theories. For the given scenario, the right-handed neutrino mass of the third generation is estimated in the margin $M_{\nu R_3} = 10^{14.9\pm0.2}$ GeV. Based on this estimate, the seesaw mechanism determines the value of lightest neutrino mass to $m_{\nu_1} = 10^{-2.5\pm0.3}$ eV.

Thus the combination of SO(10) symmetry, *i.e.* universal scalar masses and gauge couplings, and the seesaw mechanism leads, besides the high-scale SUSY parameters, to the determination of the heavy Majorana mass $M_{\nu_{R3}}$ of the third generation and, in a consecu-

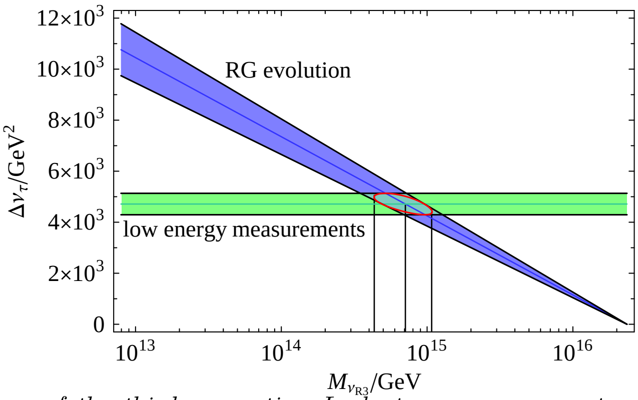

Figure 2: *Shift Δ_{ν_τ} of the third generation L slepton mass parameter generated by loops involving heavy r.h. neutrinos. The blue wedge corresponds to the prediction from the renormalization group, whereas the green band is determined by low-energy mass measurements.*

tive step, to an estimate value of the lightest neutrino mass m_{ν_1} in hierarchical theories.

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